Improving the design of rockfall protection fences using a reliability-based approach

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ABSTRACT: This study proposes a reliability-based approach for the design of rockfall protection fences. From rockfall simulations using the code Rockyfor3D is deduced the probabilistic modelling of the impact angle and impact velocity of rocks. A discrete element model represents a low energy fence (software Yade-dem). The probability for the failure of the fence is evaluated, on a real study case, using a collocation method, based on a limited number of impact simulations.

1 INTRODUCTION

Fences are passive protection structures against rockfall hazard. They aim at stopping the rocks before reaching the elements at risk. They are composed of an interception restraining net, a support structure and connecting components, most often posts and cables depending on the impact energy of the rocks. The design of fences successively consists in quantifying their ability in intercepting the rocks and in withstanding the impact. These design phases can be referred to as functional and structural designs respectively. Both these phases are based on results from rockfall propagation simulations. Trajectory simulation tools allow assessing the statistical distributions of the passing heights and kinetic energies of the rocks at a given point on the slope corresponding to the projected location of the fence.

Despite the advances concerning the impact response of fences obtained from the numerous experimental and numerical investigations held during the last two decades, limitations concerning their design can be identified. First, the results obtained mainly concern centred impacts, by a normally impacting rock without rotational velocity. Second, improvement concerning the design of rockfall protection fences mainly concern high energies, whereas the design for energies less than 200 kJ have been insufficiently studied while they concern a large number of sites. Third, the fence design rarely considers the specific loading conditions of the fence, in terms of impact point location, impact angle, and velocity in their implantation site as obtained from rocks propagation simulations. The variability of the loading conditions is moreover generally not accounted for because it would require performing Monte Carlo simulations using numerical models of fences. Indeed, this is not possible in practice because of unaffordable computational time.

This study proposes a reliability-based approach for the design of rockfall protection fences. This work is based on a study site (section 2) where well-documented field rockfall experiments have been held by Irstea Grenoble (Dorren et al., 2006). In section 3, principles of the approach are resumed. Finally a brief probabilistic analysis is presented in section 4.

2 STUDY CASE

2.1 The rockfall protection fence

The reliability-based approach is applied to tree-supported fences intended to intercept low kinetic energy rockfall. Blocks considered are less than 1 ton in weight with velocities less than 25 m/s, the maximum block velocity in such a context, as reported in the literature (Dorren et al. 2006). Therefore, kinetic energies less than 200 kJ can be expected, which is considered a low-energy value for rockfall protection structures.

The fence is made of double-twisted wire mesh connected to an upper and a lower cables thanks to cable clips regularly spaced. Each cable extremity forms a loop around a tree-trunk, the cable dead end being secured on the cable by cable clips. The loops are closely tightened to avoid any damage to the trunk. Two rigid posts placed at each extremity of the fence, parallel to the tree trunks, maintain the distance between the upper and lower supporting cables.

Several on-site impact test campaigns were conducted on these structures validating the concept and providing data for the numerical model calibration (Lambert et al. 2010), (Bourrier et al. 2010). The distance between the trees was 22 m. The upper and lower supporting cables were 12 mm in diameter. The mesh was made of a 2.7-mm-diameter wire forming hexagons 80 mm and 100 mm in height and width respectively. The distance between the support cables, or fence height, was 3 m. The distance between the trees and the post was 3 m. These parameters were considered in the numerical model presented hereafter.

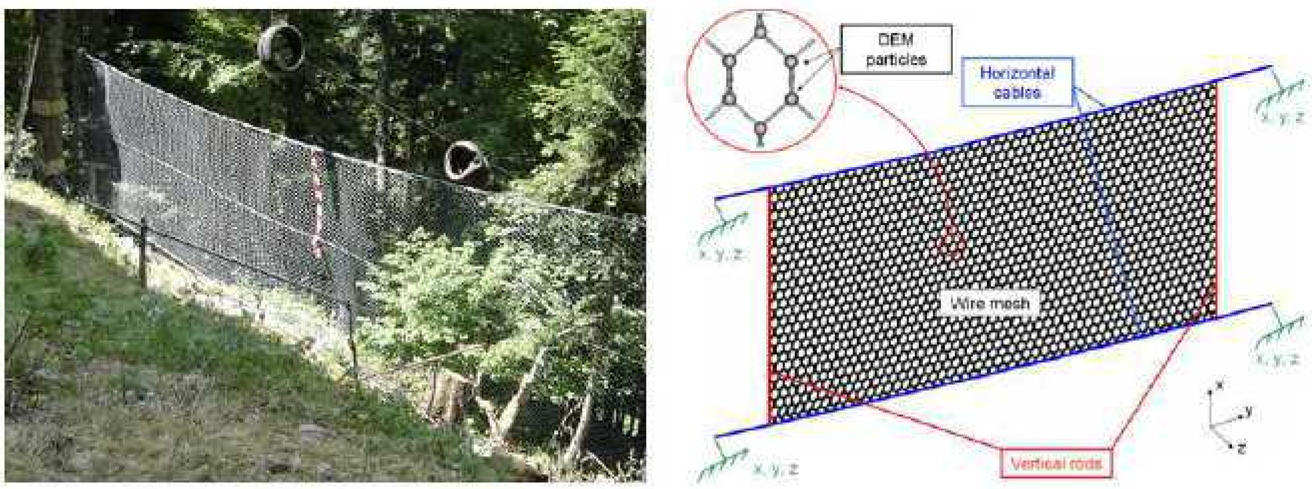

Figure 1. Tree-supported fence: experimental structure and DEM model

2.2 Numerical model of the fence

The fence was modeled accounting for the geometry of the fence, the cables and rods, and the boundary conditions (Figure 1).The structure response was simulated based on the discrete element method (DEM) (Cundall et al. 1979) using the open-source software Yade-DEM (Smilauer et al. 2010). The numerical model of the fence, and in particular of the hexagonal wire mesh, is derived from Bertrand et al. (2008). The impact by the rock block was modeled by considering a spherical element with a given mass and initial velocity. The interaction between the block and the mesh particles was modeled by contact forces considering an elastic normal contact law while neglecting the block-fence friction. The numerical model was used to investigate the influence of parameters related to the block (mass, velocity, impact point, inclination). The influence of various structural choices might also be investigated in an optimization process (single mesh dimensions, fence length and cable diameter). Nevertheless, this would be unaffordable as each DEM calculation lasts about 12 h using a classical computer, unless specific approaches are developped.

2.3 Study site

The choice was made to use an extensively documented field rockfall experimental site. The study area covers an Alpine slope ranging from 1200 m to 1400 m above sea level with a mean gradient of 38^{o} in the ’Forêt communale de Vaujany’ in France (lat. 45^{o}12′, long. 6^{o}3′). The slope surface mainly consists of rockfall deposits. The 3D rockfall simulation code Rockyfor3D was used. This software allows simulating the propagation of spherical falling blocks by successive phases of free flight and rebound on the slope surface on a digital terrain model from user-defined departure zones. The digital terrain resolution was set to 2m in this study. Additionally, the slope surface material parameters calibrated in the previous research works on the study site have been used (Dorren et al. 2006), (Bourrier et al. 2009). On the contrary, departure zones and falling rock volumes different from the previous research works have been defined. The choice of rock mass and of the location of the departure zone was made to obtain rockfall events that can potentially be stopped with low energy rockfall fences. This corresponds to impacting rock energy smaller than 50 kJ at the fence location. More precisely, the case of a 0.2 m^3 rock weighing 480 kg reactivated uphill the forest road was envisaged (Fig. 2). In the principle, such an event could in particular result from forestry works. For the purpose of the study, the element at risk to be protected was a forest road located at mid-slope in the site. The potential location of the fence was fixed between the rock release point and the forest road to be protected.

The rockfall simulation code was used to model the propagation of the rocks through the site and, in particular, the passing heights and kinetic energies of the rocks at the potential location of the fence (Fig. 3). Figure 4 reveals a significant variability of the kinematic parameters of the rocks when impacting the fence.

Developing the approach for all the variable parameters identified is tricky in practice given the large amount of random variables mentioned above and the potentially significant correlations between these variables. For the sake of simplicity, the number of random variables considered in this study was limited to the parameters that were identified to influence the most the failure of the fence, considering a centred impact. Consequently, only the impact velocity and the impact angle were considered as random variables associated with the distributions obtained in the rockfall simulations. All other kinematic parameters were set at their mean values obtained from the simulation.

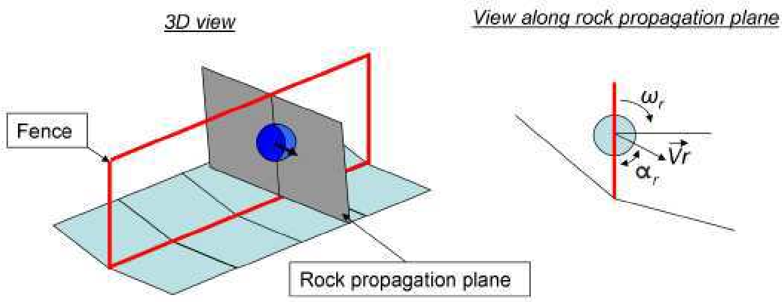

Figure 3 Parameters describing the block trajectory when crossing the fence.

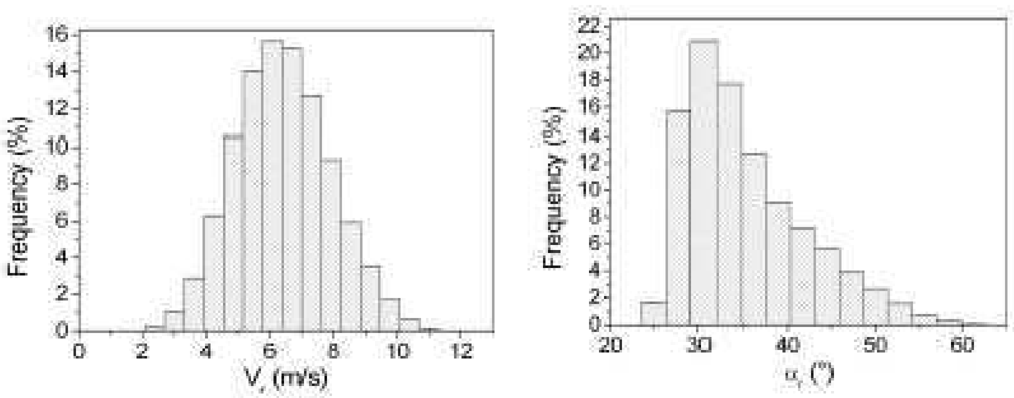

Figure 4 Block kinematics when reaching the fence obtained from rockfall simulations: distributions of the translational velocity V_r and impact angle α_r.

3 RELIABILITY-BASED DESIGN OF THE FENCE

3.1 Principles of the reliability-based approach

Let consider $G = V_{z,out}/V_{z,in}$ as an estimator of the efficiency of the structure, where $V_{z,in}$ and $V_{z,out}$ are the components along the horizontal axis of the block velocity before and after contact with the fence, respectively. $G \leq 0$ means that the block is stopped (safety domain). On the contrary, the block has cleared the fence if $G > 0$ (failure domain). Such an estimator is deduced from past experimental and numerical works on this type of structure (Bourrier et al. 2010, Lambert et al. 2010).
This section presents the methodology to characterize the probability P_f = Prob($G > 0$) for the fence failure using the DEM model of the fence. Contrary to classical Monte Carlo simulations, the approach proposed does not require covering all the parameter ranges. On the contrary, it allows calculating P_f using only a reduced number of impact simulations, which ensures its practical feasibility. Besides, the loading parameters to be used in the simulations (incident angle, block velocity...) do not result from a user choice: the method allows determining these values to get statistically relevant responses of the structure.
The variability of the impact conditions can be characterized by a set of uncertain parameters y_i associated with the properties of the block (mass, shape) and its trajectory (impact velocities, impact point location). These parameters can be considered as the different components of a vectorial random variable Y. In this work, the mechanical response of the fence is modeled by a random variable $f(Y)$ to be characterized. In this study, this response is the estimator of the fence efficiency $G = V_{z,out}/V_{z,in}$, called "performance function". Assuming that Y can be related with a standard random variable X (Gaussian), such as $Y = T(X)$, the performance function is expressed as $G = f \circ T(X)$. In case of two uncertain input parameters $(Y_1, Y_2) = Y$, the performance function G may be approximated in writing the approximation $\tilde{G}$ of G as an expansion in Lagrange polynomials (Baroth et al. 2007) of standard Gaussian random variables X_1 and X_2, such that

$$G(X) \approx \tilde{G}(X_1, X_2) = \sum_{i=1}^{N}\sum_{i=1}^{N} G_{i,j} L_i(X_1) L_i(X_2) \qquad (1)$$

where $G_{i,j} = G(x_i,x_j)$ is a set of N^2 values of G and L_i, L_j are Lagrangian polynomials ; for instance, L_i writes

$$L_i(x) = \prod_{\substack{k=1 \\ k \neq i}}^{N} \frac{x - x_k}{x_i - x_k} \qquad (2)$$

The calculation of the performance function can be envisaged for a larger number of uncertain input parameters although it will not be presented in the following. The values x_i and x_j are related to collocation points $y_i = T(x_i)$ and $y_j = T(x_j)$. The values y_i and y_j are defined depending on the statistical law associated with the random variable Y and on the number N of points considered (Baroth et al. 2007). The values of the performance function $G(x_i,x_j)$ are thus obtained from numerical simulations of impact on the fence using the set of parameters (y_i, y_j) corresponding to (x_i,x_j). Then, the numerical (and time-consuming) performance function G is approximated by the analytical function $\tilde{G}$.

3.2 Application to the study case

In the following, the influence of the impact velocity V_r and the impact angle α_r on the efficiency of the fence will be studied. These two parameters are first considered as non-correlated before accounting for the linear correlation. This aim in view, probability density functions are deduced from the trajectory analysis for the impact velocity V_r and the impact angle α_r (Fig. 4). Log-normal random variables, denoted $(Y_1, Y_2) = Y$, are chosen. This choice is a satisfying compromise taking into account the trend of histograms (Fig. 4) and preventing from negative realizations (negative impact velocities, in particular) while allowing an easy probabilistic treatment. Besides, the different values of the couples (V_r, α_r) show significant negative correlation between the two random variables (Fig. 4). For increasing values of V_r, decreasing mean values and variability of α_r are observed. This correlation can either be ignored or accounted for in evaluating the fence efficiency. In this latter case, a linear correlation can be considered, with a coefficient of -0.48. Table 2 presents means, coefficients of variation and coefficient of correlation of the random variables.

As detailed in (Baroth et al. 2006), the Gaussian standardization of Y, using the relation $Y = T(X)$, is used to apply the collocation method. One or two non correlated variables can be considered using this framework by using only the expression of Y_1 or setting the correlation coefficient ρ_{Y_1,Y_2} at nil value, respectively. A $N = 5$ points procedure has been used for analysing the fence failure probability. This means that considering two random variables are considered, the procedure requires performing impact simulations for all possible couples of the random variables, corresponding to 25 impact simulations (Fig. 5).

Table 1. Means and coefficients of variation (Cv) of the log-normal random variables associated with the velocity V_r and impact angle α_r, with correlation coefficient $\rho_{Y1,Y1}$ = -0.48.

Uncertain parameter	$Y_1 = V_r$	$Y_1 = \alpha_r$
Means	μ_{Y1} = 6.42 m/s	μ_{Y2} = 35.4°
Coefficients of variation	Cv_{Y1} = 0.25	Cv_{Y2} = 0.18

Table 2. Values of the impact velocity $V_{r,}$ variable in the simulations

$V_{r,i}$ (m/s)	3.1	4.47	6.23	8.69	12.55
$\alpha_{r,j}$ (°)	20.72	27.22	34.81	44.53	58.49

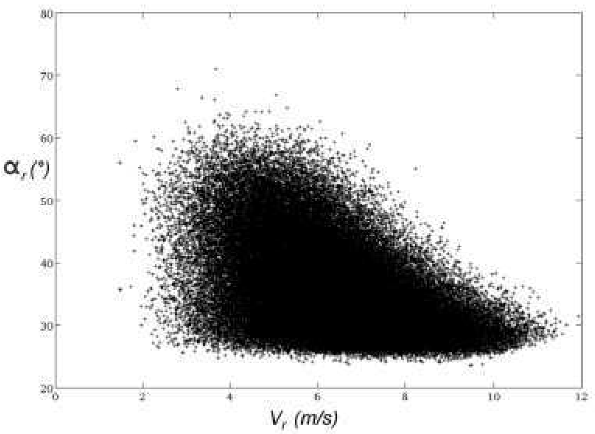

Figure 4 Couples (V_r, α_r) obtained from rockfall simulations using RockyFor3D.

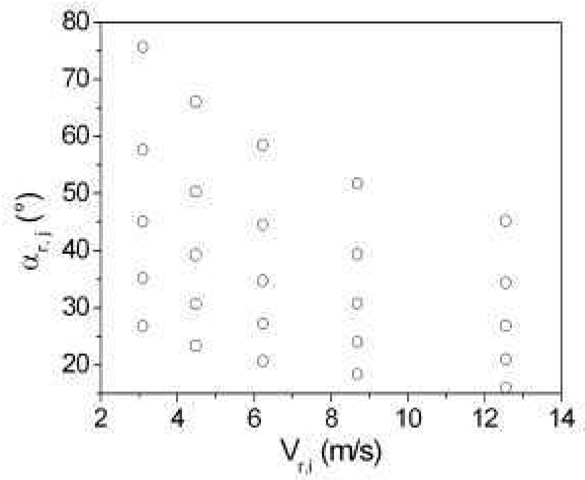

Figure 5 Couples (V_r, α_r) used for the generation of the simulation sets of 25 DEM impact simulations

4 PROBABILISTIC ANALYSIS OF THE FENCE EFFICIENCY

The set of 25 simulations allows characterizing the cumulative distribution of G considering the linear correlation existing between the two variables. The fence failure probability in such a case is calculated from the cumulative distribution functions of G (Fig. 6). The comparison with the case where random variables are considered non-correlated plotted on the same figure, shows that integrating the correlation is slightly conservative as the probability for the block to clear the fence is larger when correlated variables are considered. Without correlation, this probability P_f = Prob(G > 0) is 4.2 % whereas it is 7.6 % considering the correlation.

This failure probability can be used to assess the residual hazard down the protective structure. And, in a practical context, this failure probability value may be considered unacceptable, requiring redesigning the structure to increase the maximal kinetic energy it can withstand.

5 CONCLUSIONS

This study has proposed a reliability-based approach for the design of rockfall protection fences. A probabilistic modelling of the impact angle and impact velocity of rocks has been deduced from rockfall simulations using the code Rockyfor3D. A discrete element model represents a low energy fence (software Yade-dem). The probability for the failure of the fence is evaluated using a collocation method, based on a limited number of impact simulations, focusing on tow random variables : impact velocity and impact angle.

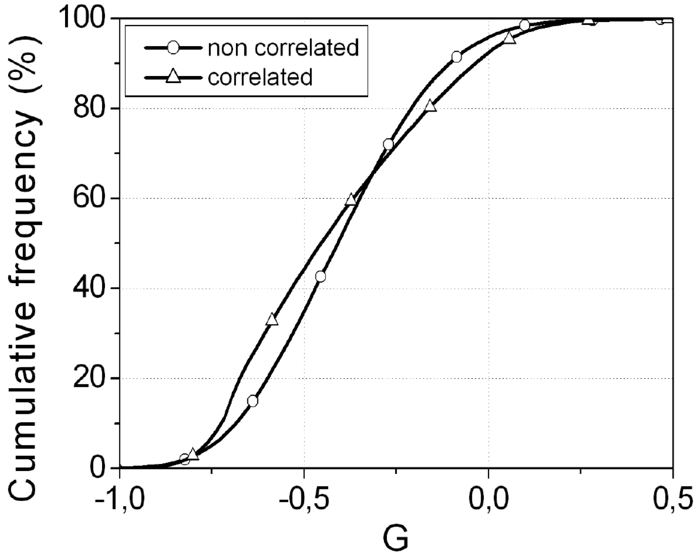

Figure 6. Cumulative distribution of the performance function G considering V_r and α_r as the only random variables.

The two random variables obtained in the simulations were assumed to follow lognormal distributions. 25 impact simulations using the discrete model of the fence allow characterizing probabilities of failure of the fence in different cases; the proposed method allowed calculating the probability for the failure of the fence for two correlated log-normal random variables. The influence of using other probability laws could also be investigated using the same 25 calculations.

The results obtained for these indicators show that taking into account the variability of both variables significantly increases the probability for the fence failure and that accounting for the correlations between the variables is also all the more important. Indeed, the probability for the failure of the fence is higher when considering the variability of the two correlated random variables.

This approach appears promising in terms of fence design improvement for it allows investigating the influence of many variables. It also allows improving the quantification of the residual hazard in the site after installing the structure. Nevertheless, future investigations should consider the influence of other parameters: the impact point location on the fence and the orientation of the block with respect to the fence perpendicular axis.

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